NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 1-96

EVALUATION OF THE SCUBAPRO MK 10 AND MK 20 SCUBA REGULATORS FOR USE IN COLD WATER

J.R. CLARKE AND M. RAINONE

JANUARY 1996

NAVY EXPERIMENTAL DIVING UNIT

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NEDU tested the breathing effort and susceptibility to freeze-up of the Scubapro MK10 and MK20 SCUBA regulators. The regulators were tested in 28°F (-2°C) salt water, at depths to 198 fsw (60.7 msw). Five samples of each model were tested. The probability of regulator failure was computed from the number of cold induced incidents, and the time to failure for each incident. Under these rigorous conditions, the probability of failure for the Scubapro MK20 was relatively high, but was lower than in the MK10. There were a large number of high breathing pressure events during the resistive effort measurements in both regulators at a 1500 psi supply pressure. Performance was improved at 500 psi supply pressures. Neither the Scubapro MK10 nor the MK20 is recommended for Navy use in sea water at 28°F and depths to 190 fsw.

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GLOSSARY

ANU	Authorized for Navy Use List (NAVSEAINST 10560.2 series)
bar	Metric unit of pressure conveniently sized for supply pressures. One bar = 100 kPa, or 14.5 psi.
cmH_2O	A metric expression of static pressure head. One cmH_2O = 0.01 meters of pure water. In pressure equivalents, 1 cmH_2O= 0.736 torr, 981.8 Pa, or .0982 kPa.
fsw	Feet of Seawater, a unit of pressure. One fsw = 0.3063 msw.
incidence	The rate of occurrence of high pressure events occurring out of tests of five regulators. Expressed as a fractional value; e.g., two events out of five tests yields an incidence of 0.4.
J/L	Joules per liter, unit of measure for "Work of Breathing" normalized for tidal volume. One J/L = 1 kPa.
kPa	Kilopascals or newton/m^2, unit of pressure. One kPa ~ 10.2 cmH_2O
msw	Meters of Sea Water. One msw = 3.2646 fsw.
NAVSEA	Naval Sea Systems Command
NEDU	Navy Experimental Diving Unit
psi	Pounds per Square Inch, an English measure of pressure. One psi = 6.895 kPa. 1 bar = 14.504 psi.
$\overline{P}_V$	Volume averaged pressure, or resistive effort, otherwise known by the misnomer Work of Breathing (WOB). A computer derived estimate of total resistive respiratory effort obtained when breathing a regulator with a mechanical breathing simulator.
RMV	Respiratory Minute Volume with units of $L \cdot min^{-1}$. In scientific publications, this is referred to as expired ventilation ($\dot{V}_E$).

INTRODUCTION

The U.S. Navy has a requirement to identify open-circuit SCUBA regulators which perform reliably in 28°F (-2°C) water and depths down to 190 fsw (58.2 msw). To this end, NEDU was tasked[1] to test and evaluate production models of commercially available SCUBA regulators to determine those which best meet the U.S. Navy's requirement. This is a report on the Scubapro MK 10 and MK 20 regulators.

Scubapro, a division of Undersea Industries Inc. (Rancho Dominguez, California) provided five samples of both the MK 10 and MK 20 for evaluation. The diver adjustable second stage regulator, the M5 Polar, is common to both regulator assemblies. The first stage of the MK 10 is a balanced flow-through piston design, with 5 low pressure (LP) ports on a 360 degree swivel and 2 high pressure (HP) ports, and a protective boot for cold water use. Intermediate pressure (IP) is between 125-145 psi. According to the factory, the MK 20 is similar, with the following exceptions:

"*Piston / Seat Alignment* - Perfect alignment and concentricity of the MK 20 piston and HP seat is guaranteed by boring the two internal body surfaces simultaneously. The seat retainer no longer is responsible for aligning the seat. This feature is unique to the MK 20 and produces precise IP stability and control.

Rounded Piston Edge - The MK 20 utilizes a new rounded piston sealing edge. The rounded and polished edge helps to reduce the cutting effect of the piston and improve IP stability.

IP Adjustment Washer - The intermediate pressure can be altered approximately 15 psi by installing / removing special washers located between the HP seat cap and the main body (3 washers max). This procedure can be done without disassembling the main housing."

For regulators designed for use in relatively warm water (>37°F), the primary criterion by which the regulators are judged during unmanned testing is their ability to meet the performance goals[2] for volume-averaged pressure ($\overline{P}_V$) or resistive effort. For diving under polar ice, however, a more important consideration than breathing effort is resistance to freeze-up. In modern regulators, freeze-up is usually manifested as free-flow due to either a second stage failure, or loss of intermediate pressure control due to failure of the first stage. On rare occasions, the first stage can fail with complete blockage of gas flow. Since freeze-up is a potentially life-threatening occurrence, we placed primary emphasis on regulator freeze-up susceptibility, with secondary emphasis on $\overline{P}_V$.

METHODS

<u>Regulators</u>

The regulators supplied to NEDU by Scubapro were 1995 models. The MK 10 Polar regulators had serial numbers 5010711191 to 5010711195, while the MK 20 Polar regulators had serial numbers 5031600493 to 5031600497. All regulators were set up according to Scubapro instructions and bench tested prior to initial cold water exposures.

Environmental Control

Test regulators were submerged in brine-filled tanks with water temperature maintained at 28° F to 31° F (-2.2° C $\pm$ 0.5° C). The brine mixture was prepared with tap water and Instant Ocean® salt mixture (Aquarium Systems, Mentor, OH). The salinity of the brine solution was approximately 45 parts per thousand to prevent ice formation on the heat exchanger coils and loss of temperature control. Salinity was measured by the refractive index of the brine using an automatic temperature compensated hand refractometer (Model 10419, Reichert Scientific Instruments, Buffalo, NY). The water content in the high pressure air supply was measured by a phosphorous pentoxide (P_2O_5) detector system, and was found to be 23 ppm, translating to a -65.5°F dew point.

"Exhaled" air from the breathing machine was heated and humidified such that the gas temperature measured at the chrome tee (connected to the mouthpiece of the second stage regulator) ranged between 10° and 20°C.

Breathing Simulator

A computer controlled electro-mechanical breathing simulator (Battelle, Columbus, OH) ventilated each regulator at respiratory minute volumes (RMV) ranging from 22.5 to 90 $L \cdot min^{-1}$, thus emulating varied diver work rates. Supply pressure to the first stage was maintained at 1500 psi (103.4 bar) for one set of tests, then reduced to 500 psi (34.5 bar) for another set. This procedure was in accordance with NEDU Test Plan 93-21, except that in this instance the regulators were warmed and dried before repeating the cold water exposure with 500 psi supply pressure[3]. Recordings of pressure-volume loops were taken at 33 fsw (10 msw) increments. Test depths ranged from 0 to 198 fsw (0 to 60.7 msw). Testing at a specific RMV/depth parameter was terminated if inhalation or exhalation pressure exceeded 4 kPa, the working limits of the pressure transducers currently used in the Experimental Diving Facility.

Statistics

Descriptive statistics were used to obtain the mean and standard deviation of the resistive effort data. The one-sided, one sample T-test was used to compare test results with the NEDU performance goal for SCUBA regulators. Examples of the application of this test is described in Chapter 7 of the NEDU Technical Manual on Unmanned Test Methods and Performance Goals[2]. Statistical significance was established at $P < 0.05$.

Freeze-Up Dive Profiles

NEDU uses two dive profiles for evaluating freeze-up susceptibility. One is a fixed depth, worst case protocol. The regulator was dived to 198 fsw (60.7 msw) and breathed at an RMV of 62.5 $L \cdot min^{-1}$ for 30 minutes. This run was repeated at 132 fsw (40.4 msw) and 33 fsw (10.1

msw). We also simulated a severe bounce dive protocol with a dive to 190 fsw (58.2 msw) for 20 min with a ventilatory rate of 50 $L{\cdot}min^{-1}$, followed by five minute decompression stops at 40, 30, 20, and 10 fsw with the same RMV.

Failure Probability Determination

For freeze-up susceptibility tests, both the number of regulators freezing and the time at which they froze were considered. Those results were empirically combined in the following manner.

$$P_f = \sum_{i=1}^{n} \left(\frac{n^{-1} \cdot E_i}{t_i^k} \right) \qquad (1)$$

where P_f is the probability of failure (ranging between 0 and 1), n is the number of regulators, E is a binary event equal to 0 if there is no failure and 1 if the regulator fails, t is the time to failure in minutes, and k is an empirical constant = 0.3, chosen to provide reasonable probabilities. By NEDU convention, n = 5. If all 5 regulators freeze after 1 minute, then

$$P_f = \left(\frac{0.2 \cdot 1}{1^{0.3}} + \frac{0.2 \cdot 1}{1^{0.3}} + \frac{0.2 \cdot 1}{1^{0.3}} + \frac{0.2 \cdot 1}{1^{0.3}} + \frac{0.2 \cdot 1}{1^{0.3}} \right) = 1.0$$

If no regulators fail, then $P_f = 0$. If 2 freeze, one at 18 minutes and one at 28 minutes, then $P_f = 0.158$. When ranking the desirability of various cold water regulators, a regulator with a P_f of 0.158 would be preferred over one with a P_f of 0.34.

$$P_f = \left(0+0+0+\frac{0.2 \cdot 1}{18^{0.3}}+\frac{0.2 \cdot 1}{28^{0.3}}\right) = 0.158$$

The above empirical probability estimation is nothing more than a way of quantitatively comparing, or of ranking, various regulators. It does not estimate the actual probability of freeze-ups during an open water dive. That probability is dependent upon the duration of the dive relative to the expected time of regulator freeze-up.

Resistive Effort

$\overline{P}_V$ levels are a computer derived estimate of total respiratory effort obtained when breathing a regulator with a mechanical breathing simulator, measured in kPa (or in more cumbersome terms, joules per liter, J/L). $\overline{P}_V$ averages were derived from the mean of tests on up to five individual regulators for each model.

RESULTS

Freeze-up Susceptibility

All five of the MK 10 regulators began free-flowing during the fixed profile at 198 fsw, as well as during the bounce dive profile. The time to free-flow in the fixed profile ranged from 5 to 20 min, with a median time of 13 min. The free-flow times during the bounce dive profile ranged from 5 to 34 min, with a median of 19 min. Two MK 20s free-flowed prior to completion of the fixed profile, and three free-flowed during the bounce dive profile. From Equation (1) the P_fs for the Scubapro MK 10 and MK 20 regulators were as follows:

Table 1. Freeze-up susceptibility.

Regulator	Fixed Profile	Bounce Profile
MK 20	0.149	0.274
MK 10	0.459	0.446

Resistive Effort

Virtually all of the runs at the 1500 psi supply pressure were aborted by the operators to protect the test instrumentation whenever the inhalation or exhalation pressures exceeded 4 kPa. At 500 psi, performance in cold water was improved. The mean resistive efforts for the MK 10 and MK 20 regulator at 500 psi (34.5 bar) supply pressure are shown in Figure 1. The horizontal lines in each panel represent the NEDU performance goal[2] for SCUBA regulators, 1.37 kPa.

The plotted means represent the average for all runs that were completed by all 5 regulators. Typically, the $\overline{P}_V$ of greatest interest is that at a RMV of 62.5 L·min^{-1} (upward pointing triangles) at the deepest depth. Under those conditions, all five of the MK 10 regulators provided resistive efforts below the 1.37 kPa goal. The MK 20 was not as successful. At shallow depths, however, the resistive efforts for the MK 20 were clustered more tightly around low values than they were for the MK 10.

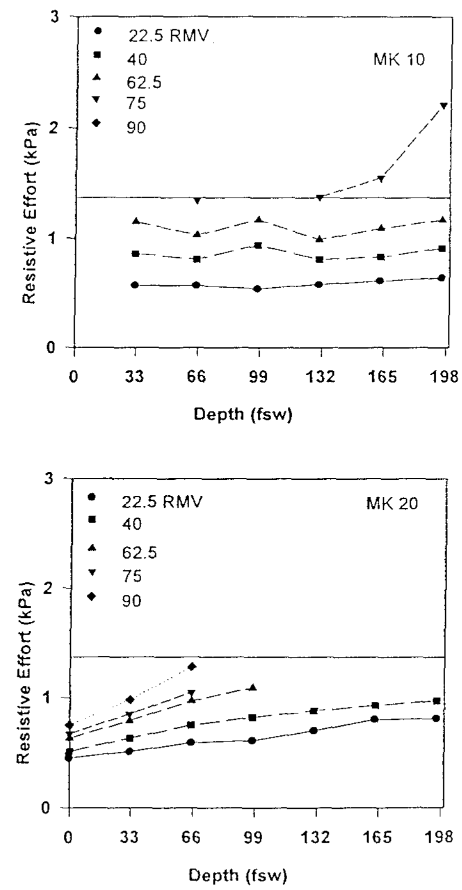

Figure 1. Resistive effort (WOB) at 500 psi supply pressure.

Event Incidence in Resistive Effort Tests

The primary purpose of resistive effort measurements was to describe the breathing effort of the regulators. However, two events could hamper those measurements; one is excessively high ventilatory pressures, and the other is regulator free-flow. The two events are considered of equal importance since both could be due to the effects of cold water.

Figures 2 and 3 are plots of the dependent variable, event incidence with a 1500 psi (103.4 bar) supply pressure, against the independent variables mass flow rate and test sequence for the regulators. Incidence is the fraction of all runs marred by a high pressure event requiring the run to be aborted. The independent variables are located on the horizontal plane.

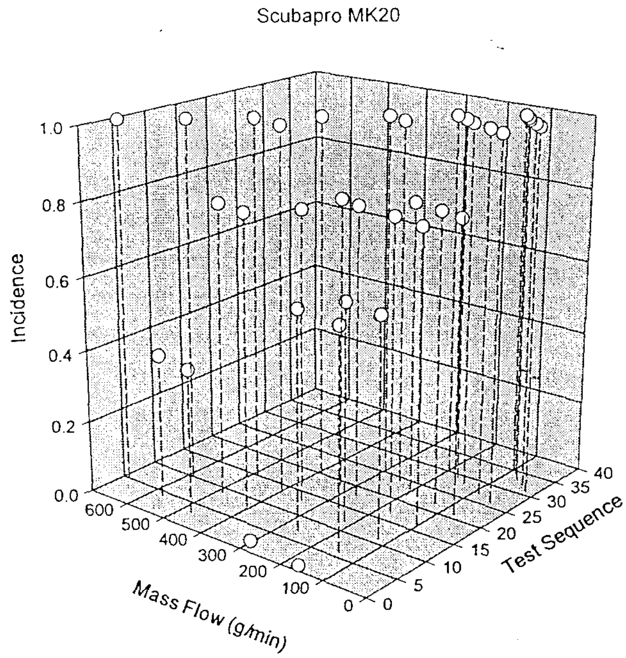

Figure 2. Incidence of high pressure events during resistive effort testing at 1500 psi supply pressure in the MK 20.

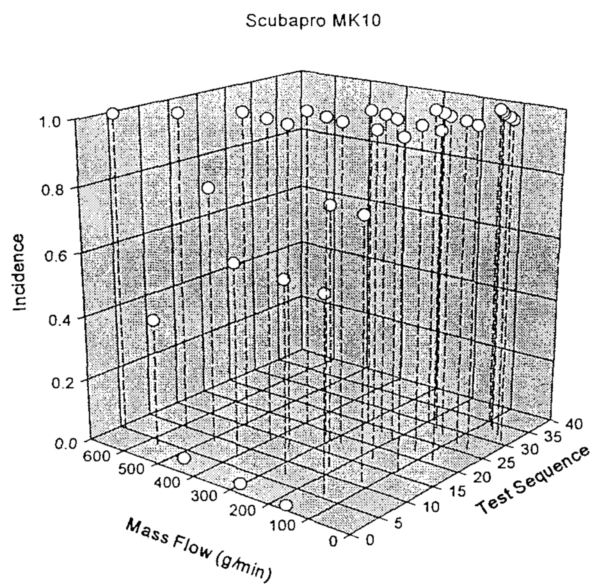

Figure 3. Incidence of high pressure events during resistive effort testing at 1500 psi supply pressure in the MK 10.

The test sequence represents the order in which tests were conducted on each regulator. Each test began at 190 fsw with an RMV of 22.5 $L \cdot min^{-1}$. RMVs were increased sequentially through 90 $L \cdot min^{-1}$, and then the chamber was brought up to the next shallower depth before the RMVs were repeated. Consequently, tests at the surface and 90 $L \cdot min^{-1}$ were the last runs conducted. For both regulators, the entire test sequence took between 1 hr and 1 hr 15 min. Therefore, each sequence number represents an interval of about 2 min.

Mass flow, with units of grams per min (g/min), is shown on the second horizontal axis. Mass flow is defined as:

$$\dot{M} = \rho \cdot RMV \cdot \frac{P_{amb}}{P_0}$$

where ρ is gas density in g/L at 1 atm absolute and 0° C, RMV is ventilation in $L \cdot min^{-1}$, and P_{amb} is ambient pressure in absolute units. P_0 is the absolute pressure at 1 atm, a factor required to generate a dimensionless pressure ratio. Mass flow rate reflects the mass of gas flowing through the regulator each minute.

Figures 2 and 3 demonstrate that at 1500 psi, both regulator models are likely to yield high respiratory pressures as both time and mass flow rate increase. Other than the first few minutes of the dives, there were no apparent safe zones within the graph where event incidence was zero.

DISCUSSION

Although the Scubapro MK 20 was less likely to fail the freeze-up susceptibility tests than the MK 10 regulators (Table 1), neither regulator performed particularly well when compared to other cold water regulators recently tested by NEDU[4].

The resistive effort studies primarily examine breathing resistance. However, breathing performance studies have induced free-flow due to freeze-up in these and other regulators. For that reason, NEDU uses three dimensional plots such as figures 2 and 3 as an adjunct to the standard freeze-up evaluation. These plots show that with supply pressures corresponding to a half empty cylinder, the probability of encountering remarkably high respiratory pressures is very high, almost independent of the duration of the dive. To explain the improved regulator performance in cold water with lower supply pressures than at higher pressures, we can only speculate that the adiabatic cooling associated with a first stage pressure drop from 1500 psi to 145 psi may have hindered first stage performance compared to the pressure drop from 500 to 145 psi. This implies that with full bottles, the regulator performance may have been even worse than at 1500 psi. This possibility was not tested. This difference between 1500 and 500 psi tests has been observed in other tests of cold water regulators[4].

The slight superiority of the MK 20 over the MK 10 is manifested not only in the freeze-up susceptibility tests, but also in the resistive effort values (Figure 1) at shallow depths and low bottle pressures. Interestingly, at depths approaching 200 fsw, more of the MK 10s functioned uneventfully than did the MK 20s. At 1500 psi supply pressures, the differences in event incidence between the two regulators was not remarkable (Figure 2 and 3).

RECOMMENDATION

On the basis of the above tests, the Scubapro MK 10 and MK 20 regulators are not recommended to be authorized for Navy use (ANU) in water temperatures of 28°F.

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